ET LOX Feedline Bellows Baseline vs Drip Lip Testing Consultation Report

September 2005

VOLUME I: REPORT

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Volume I: Report

1.0 Authorization

ITA #: 04-095-I	
Initiator Name: Ralph Roe	**Initiator Contact Info:** RALPH.R.ROE@nasa.gov 757-864-2400
Short Title: ET LOX Feedline Bellows Baseline vs Drip Lip Testing	
Description: Develop and conduct tests to determine the integrity of ice that forms at the LOX feedline bellows area comparing the original beveled design to the new 10 degree drip lip design for the purpose of evaluating debris potential during launch.	
Date Received: December 13, 2004	**Date A/I/C Initiated:** December 13, 2004
Initial Evaluator Assigned: Approved Out-of-Board	**Initial Evaluator Contact Information:** N/A
Lead Assigned: Mike Kirsch	**Lead Contact Info:** mike.t.kirsch@nasa.gov 505-524-5517

2.0 Signature Page

NESC Technical Evaluation Team

Mike T. Kirsch, NESC Lead	Peggy Chun
Jeff Dilg	Dan Kaufman

3.0 List of Team Members, Ex Officio Members, Advisors, Observers, and Others

Last Name	First Name	Discipline	Location
Kirsch	Mike	NESC Backup Principal Engineer	WSTF
Chun	Peggy	NESC Systems Engineering Office	LaRC
Dilg	Jeff	MSFC Structures	MSFC
Kaufman	Dan	Vibration/Acoustics	GSFC
Parsons	Vickie	Statistics	LaRC

4.0 Executive Summary

The NASA Engineering and Safety Center (NESC) was asked to consult with the Space Shuttle Program (SSP) ET Project Office and Systems Engineering and Integration Office (SEIO) on the planned tests to develop flight rationale for the ET LOX Feedline Bellows drip lip foam configuration. The objective of the test was to characterize the liberation of ice between the drip lip and non-drip lip foam configurations. The tests characterized loss of ice as a function of time between the two configurations. However, uncertainty in the data, and other ET considerations allowed sufficient time in the schedule for the heaters to be installed in the bellows, thus preventing the formation of ice altogether. This negates the need for drip lip versus non-drip lip ice liberation characterization data for flight rationale.

5.0 Consultation Plan

The following are the major activities of the NESC consultation:

Milestone	Date
Project Kick-Off via Ralph Roe and Rick Gilbrech emails	December 13, 2004
Technical Interchange Meeting SEIO, Huntsville, AL	January 5 – 7, 2005
Review of Test Plan	March 16, 2005
Discussion of Test Plan comments with SSP	March 21, 2005
Status Report to the NESC Review Board (NRB)	April 7, 2005
Decision to fly heaters as Bellows ice prevention	April 29, 2005
Final Report to NRB	October 6, 2005

6.0 Description of the Problem, Proposed Solutions, and Risk Assessment

Ice is known to accumulate, prior to launch, at the bellows locations of the LOX feedline during ET propellant tanking operations. The ice represents a debris threat to the Shuttle components. Figure 6.0-1 shows the location of the LOX feedline relative to the major Shuttle components. The LOX feedline consists of various tubes, elbows, and Ball Strut Tie Rod Assemblies (BSTRA) that feed LOX from the LOX tank to the Orbiter's umbilical. The BSTRAs function as universal joints to allow the feedline to accommodate deflection due to aero loading, pressure loading, and vehicle motions. The forward two BSTRAs are internal to the Intertank. Due to the Intertank's pre-flight purged environment, bellows icing is not a concern. However the BSTRAs, at ET longitudinal stations 1106, 1979, and 2026, are susceptible to substantial icing, due to local condensation and condensation run-off. Because of its forward location, the BSTRA at station 1106 is the most critical from a debris standpoint.

Figure 6.0-2 shows the ice that forms during the filling of the ET prior to launch. Figure 6.0-3 shows a cross-section of the original bellows foam configuration. The ET Project Office redesigned the thermal protection system rain shield, changing the shape to create a drip lip configuration. Figure 6.0-4 shows the bellows with the additional drip lip configuration. Figure 6.0-5 provides a photo of drip lip versus non-drip lip ice under a variety of environmental conditions. The columns represent the growth of ice under identical environmental conditions. The percent at the bottom of the column represents the percent loss of ice by mass between the two configurations. Although the redesign greatly reduced the build-up of ice that occurs around the bellows gap during the cryogenic tanking, ice still forms under certain on-pad environmental conditions. This condition mandates an additional ice suppression system. The ET Project Office proposed a heater design solution that prevents the formation of ice. However, at the time of this activity, the heater qualification activity was not complete, and the NESC was consulted regarding tests to compare the liberation of ice between the drip lip and the non-drip lip configuration to support STS-114 flight rationale. Figure 6.0-6 shows the bellows with the final configuration, which includes the drip lip and the heaters.

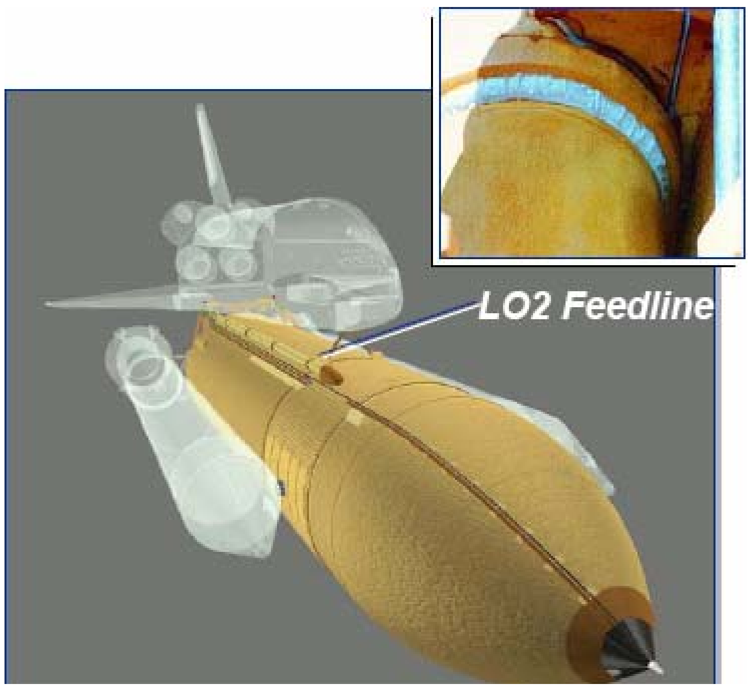

Figure 6.0-1. Liquid Oxygen Feedline on the Space Shuttle External Tank

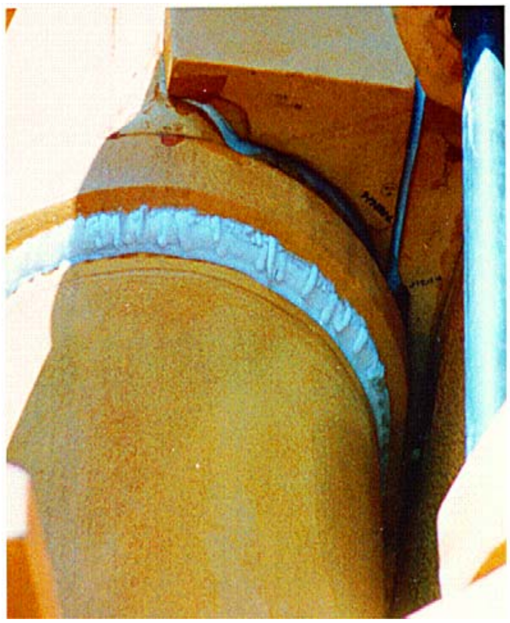

Figure 6.0-2. Bellows Ice at the LOX Feedline Bellows

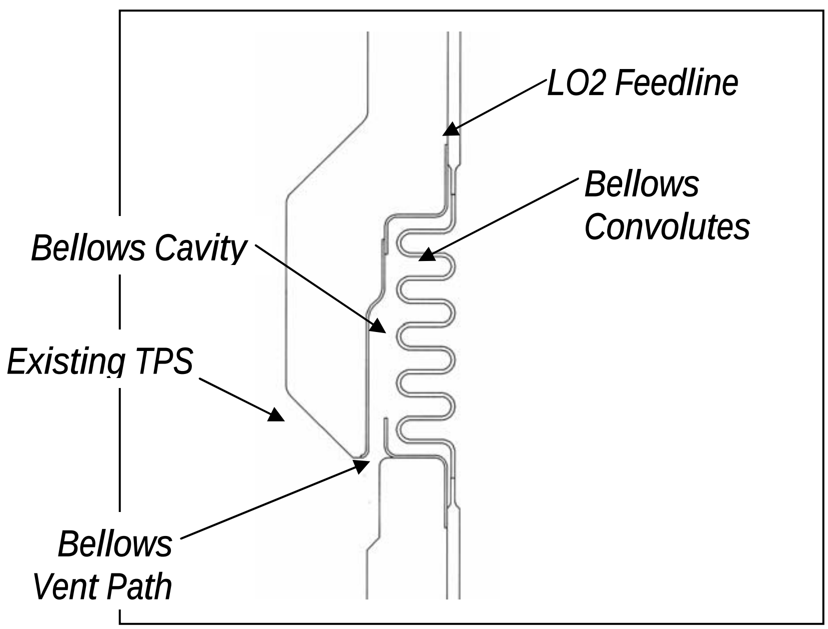

Figure 6.0-3. Cross-section of LOX Feedline Bellows without Drip Lip Configuration

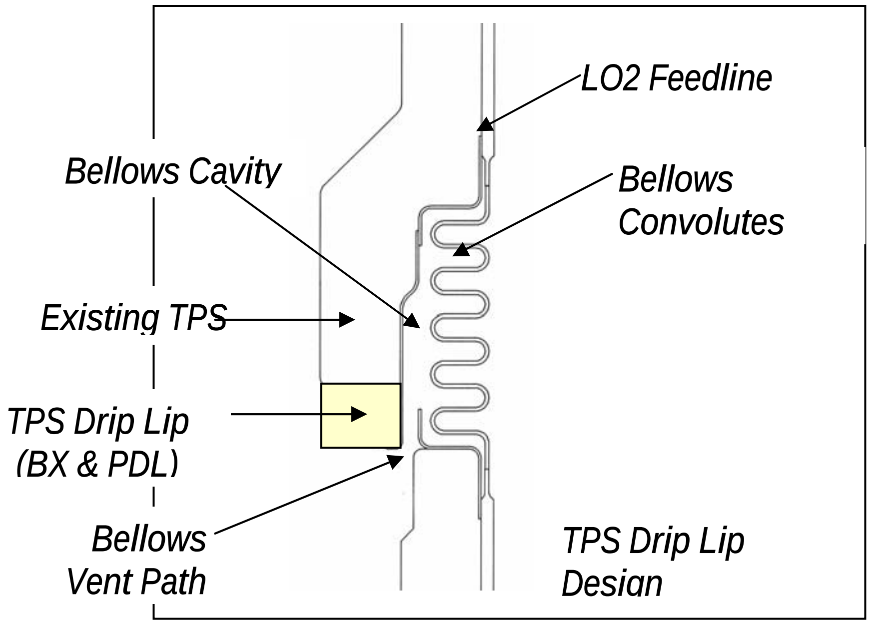

Figure 6.0-4. Cross-section of LOX Feedline Bellows with Drip Lip Configuration

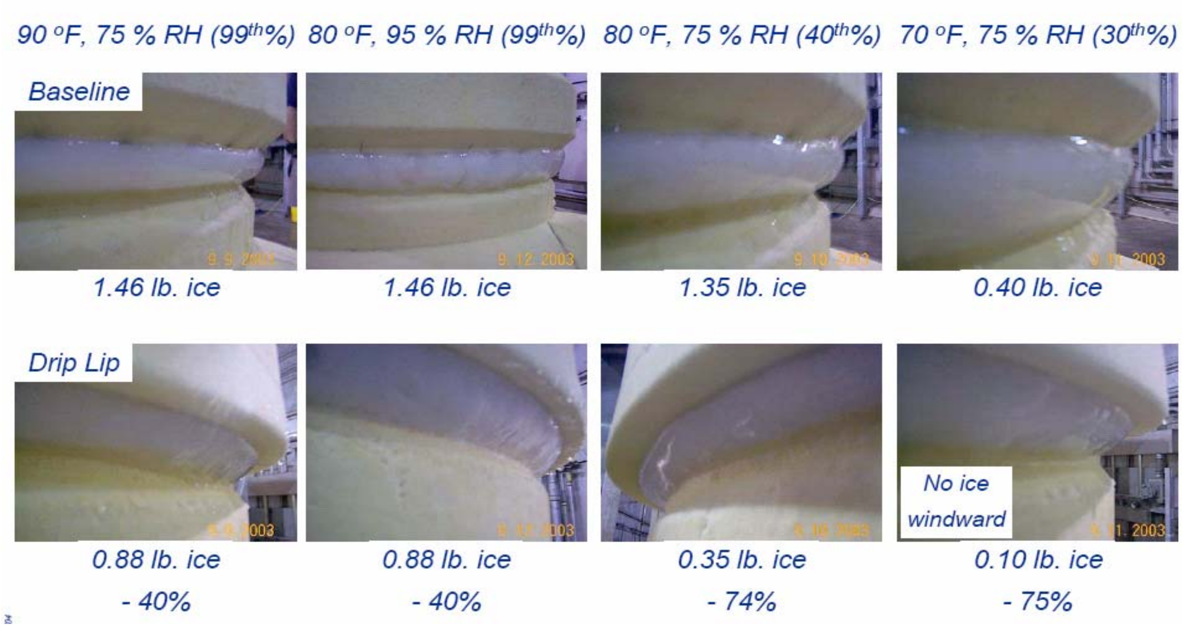

Figure 6.0-5. Drip Lip vs Non-Drip Lip Ice Formation

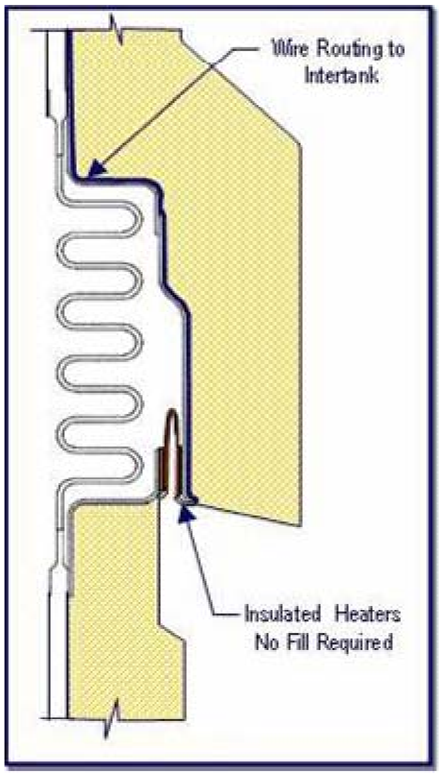

Figure 6.0-6. Cross-section of LOX Feedline Bellows with Drip Lip Configuration and Heaters

7.0 Data Analysis

The SSP, ET Project Office and SEIO, developed a detailed test plan to characterize the ET ice liberation for all pre-flight and ascent environmental conditions. The test plan is “ET Return to Flight Test Plan LOX Feedline Bellows Ice Liberation Test 809-9735.” The environments of interest included:

- Low frequency transient vibration (primarily lift-off).
- Broad Band Acoustics (lift-off and boost).
- Quasi-static angulations of the BSTRA (pre-flight, lift-off and boost).
- Thermal environment pertinent to ice generation (pre-flight).

The test system included a full scale BSTRA article with feedline segments, mounted within a test fixture to simulate bellows articulation during feedline filling. The system was then secured to a vibration fixture to simulate pre-flight and flight vibration loads. The test article was filled and pressurized with Liquid Nitrogen to achieve the LOX temperature. The test article and vibration fixture was located within an acoustic chamber with humidity and temperature control.

The consultation team reviewed a number of iterations of the test plan prepared by the SSP as well as the results from each of the tests. With each review, comments were supplied from the consultation team to the SSP for discussion, and changes were incorporated where appropriate. The intent of the SSP was to anchor the test to the flight environment by comparing flight photographs of the aft bellows after ET separation to the post test photos of the bellows test article. This was eventually abandoned, because the aft bellows test environment resulted in foam damage to the bellows test article.

In total, 8 different tests were used to characterize the ice liberation. The strategy was to characterize the loss of ice from the drip lip and non-drip lip under hard ice and soft ice conditions.

- 4/22/05 Drip Lip, Soft Ice.
- 4/23/05 Drip Lip, Hard Ice (Data missing from one high speed camera).
- 4/25/05 No Drip Lip, Soft Ice.
- 4/27/05 No Drip Lip, Hard Ice.
- 4/28/05 No Drip Lip, Soft Ice.
- 4/29/05 No Drip Lip, Hard Ice (90 percent RH).
- 5/2/05 Drip Lip, Soft Ice.
- 5/3/05 Drip Lip, Hard Ice (90 percent RH).

Additionally, members of the test team observed specific tests, and the results of the individual tests, to independently evaluate the ice liberation studies.

There were a number of test days in which the tests were aborted due to various anomalies. These included the following:

- 4/15/05 No Drip Lip, Hard Ice
  Aft Articulation, Max Acoustics full duration (experienced foam damage)
- 4/20/05 Drip Lip, Soft Ice
  No Camera Data
- 4/21/05 Drip Lip, Soft Ice
  Facility Failure
- 4/26/05 No Drip Lip, Soft Ice
  Facility Shut Down

The data was evaluated by looking at photographic evidence between the drip lip and non-drip lip articles and equivalent times during the test. Additionally, plots of ice mass loss versus time were prepared based on visual observation of test video. The mass values were calculated using volumes determined by video, multiplied by a single density regardless of whether the ice was hard or soft. In reality, the soft ice has a lower density and is less of a concern. Figure 7.0-1 presents the photographic data for hard ice. Figure 7.0-2 presents ice mass loss versus time for hard ice. Figure 7.0-3 presents the cumulative mass of lost ice versus time for hard ice. Figure 7.0-4 presents the photographic data for soft ice. Figure 7.0-5 presents ice mass loss versus time for soft ice. Figure 7.0-6 presents the cumulative mass of lost ice versus time for soft ice.

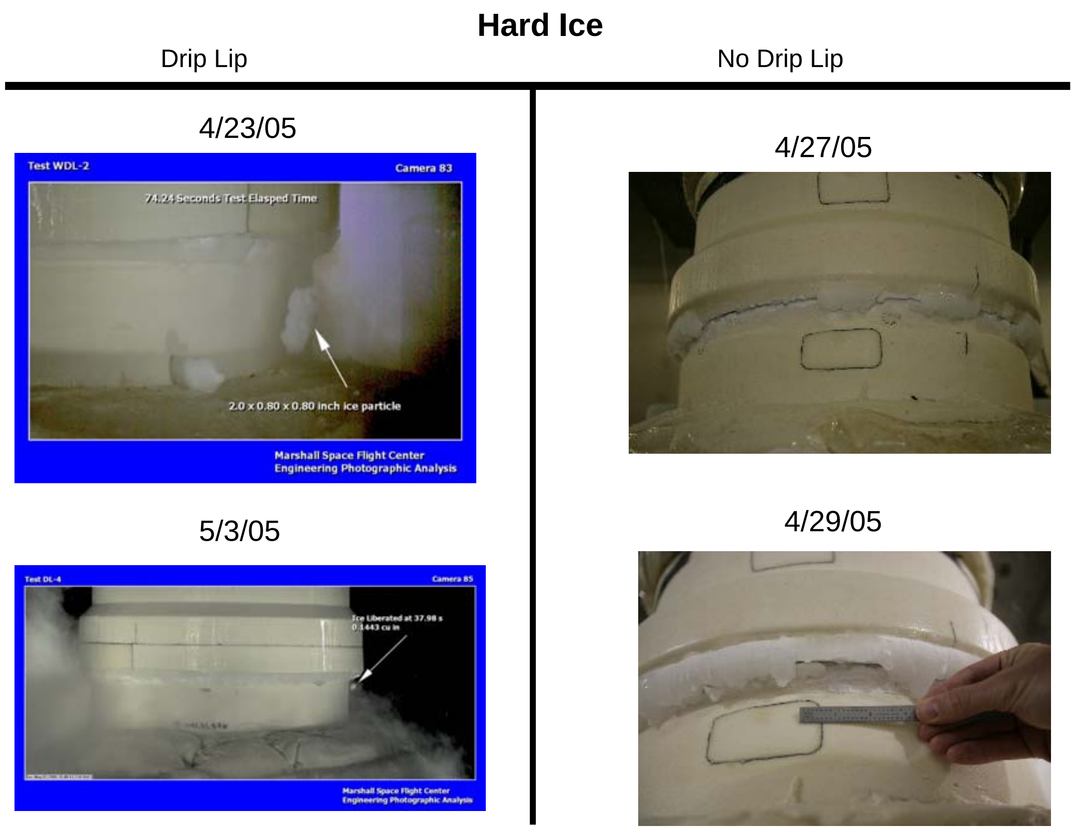

Figure 7.0-1. Photographic Data for Hard Ice

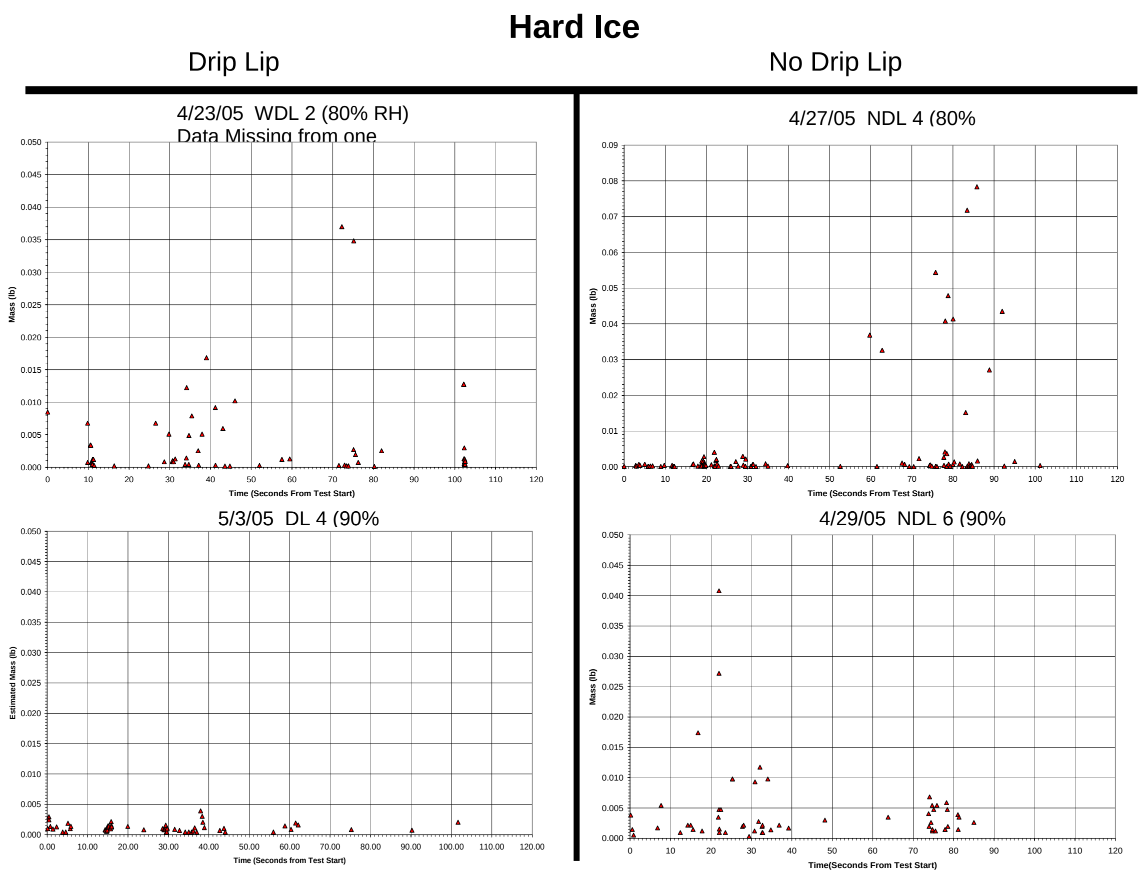

Figure 7.0-2. Ice Mass Loss Versus Time for Hard Ice

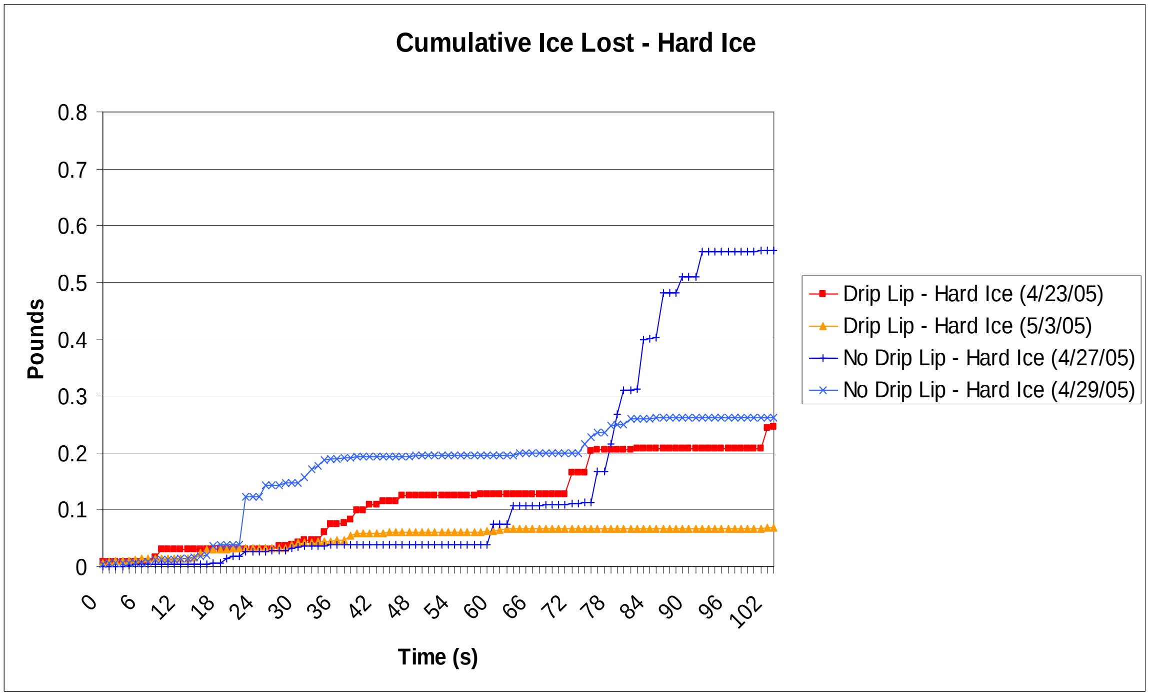

Figure 7.0-3. Cumulative Mass of Ice Lost Versus Time for Hard Ice

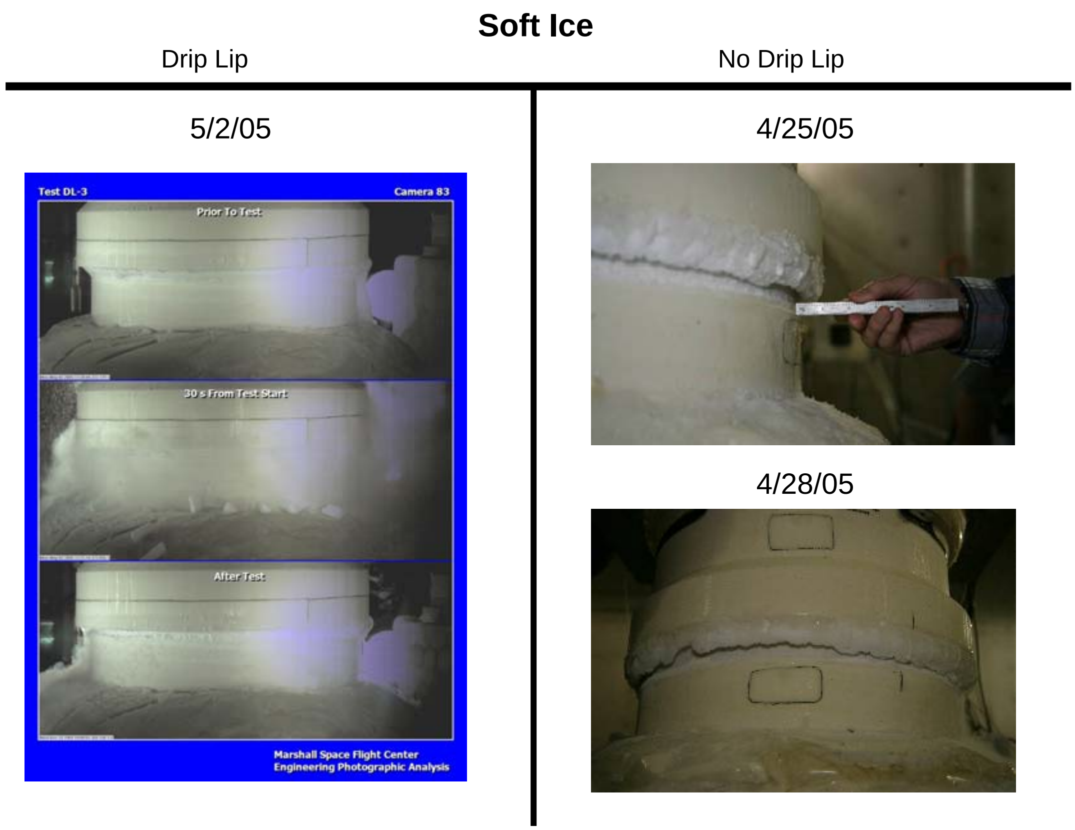

Figure 7.0-4. Photographic Data for Soft Ice

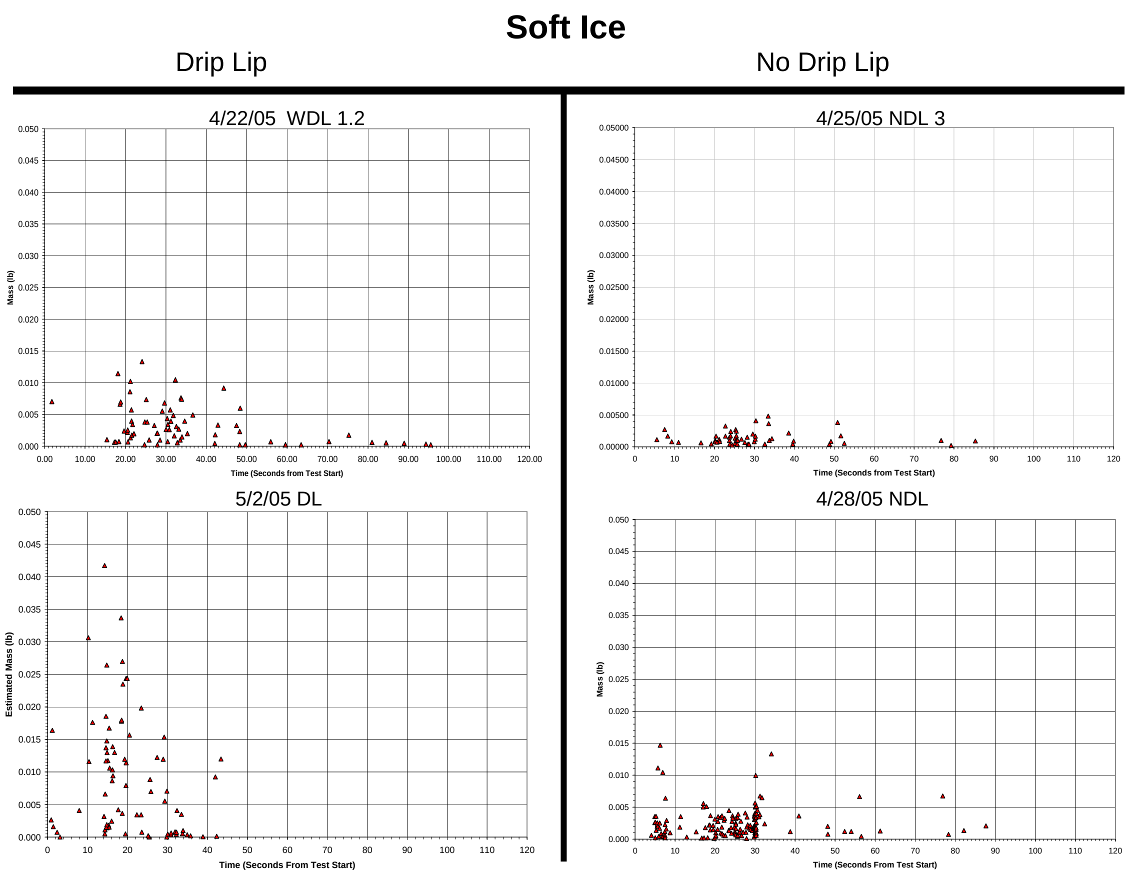

Figure 7.0-5. Ice Mass Loss Versus Time for Soft Ice

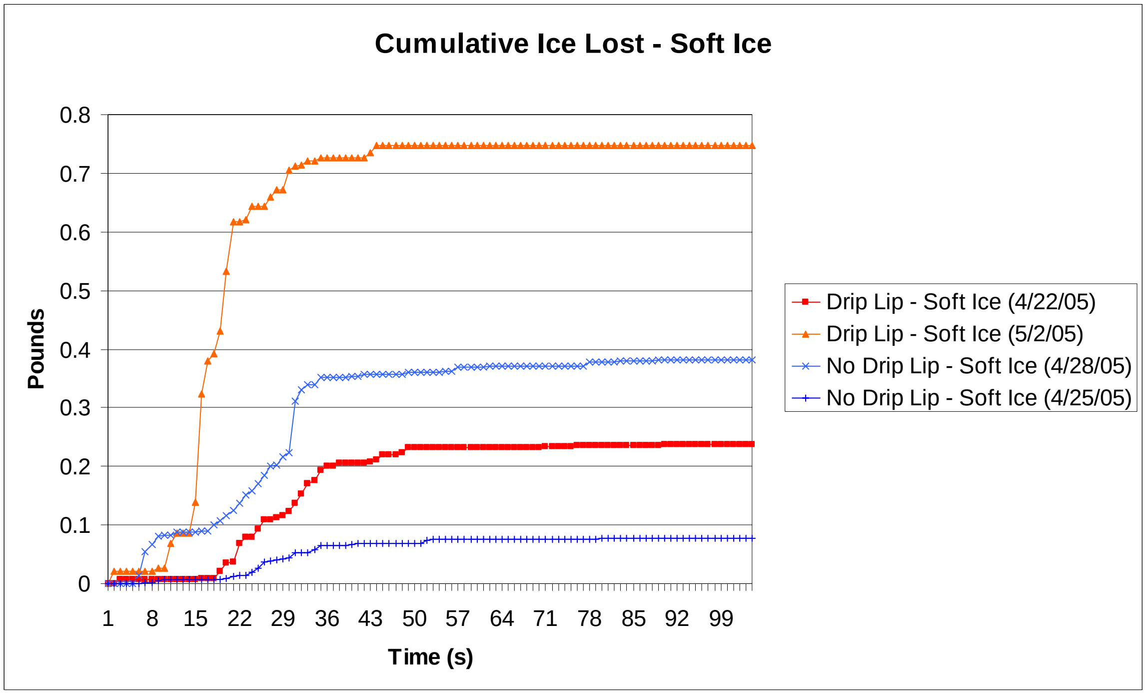

Figure 7.0-6. Cumulative Mass of Ice Lost Versus Time for Soft Ice

8.0 Findings, Root Causes, Observations, and Recommendations

The SSP engaged in a design verification review on April 28 and 29, 2005. During the review the results of the STS-114 tanking test were considered. Based on the failure of two ET Engine cutoff sensors, and based on the lack of maturity of proposed ice mitigation strategies, a SSP decision was made to roll the Space Shuttle back to the Vehicle Assembly Building (VAB) for the installation of heaters in the bellows joint. The heaters prevent the formation of ice, and therefore, negate the need for the comparison of ice liberation between the drip lip and non-drip lip configurations.

The consultation team had many concerns regarding the test setup, the statistical reliability of the data, and the relevance of the test environment to the flight environment. Although the SSP desired the use of mass lost versus time data, the team was focused on a relative comparison of drip lip and non-drip lip performance. Additionally, because damage was sustained to the test article during the aft bellows environmental loads, the tests were not grounded to the flight environment through the flight photos.

If this data or a version of this test is used for future ice liberation studies, it is recommended that the test environment be validated against the flight environment and the number of tests for a given condition be increased to establish statistical significance of the data.

9.0 Lessons Learned

There were no lessons learned during this consultation.

10.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established during the assessment/inspection by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment/inspection that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur.
Problem	The subject of the independent technical assessment/inspection.
Recommendation	An action identified by the assessment/inspection team to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible C/P/P/O in the preparation of a corrective action plan.
Root Cause	Along a chain of events leading to a mishap or close call, the first causal action or failure to act that could have been controlled systemically either by policy/practice/procedure or individual adherence to policy/practice/procedure.

11.0 List of Acronyms

BSTRA	Ball Strut Tie Rod Assemblies
ET	External Tank
GSFT	Goddard Space Flight Center
LaRC	Langley Research Center
LOX	Liquid Oxygen
MSFC	Marshall Space Flight Center
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
RH	Relative Humidity
SEIO	System Engineering and Integration Office
SSP	Space Shuttle Program
VAB	Vehicle Assembly Building
WSTF	White Sands Test Facility

12.0 Minority Report

There were no dissenting opinions in this Consultation Report.

Volume II: Appendices

Appendix A. NESC Request Form (NESC-PR-003-FM-01)

NASA Engineering and Safety Center
Request Form

Submit this ITA/I Request, with associated artifacts attached, to: **nrbexecsec@nasa.gov**, or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681

Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt		
Received (mm/dd/yyyy h:mm am/pm) 12/13/2004 12:00 AM	Status: New	Reference #: 04-095-I
Initiator Name: Mike Kirsch	E-mail: MIKE.T.KIRSCH@nasa.gov	Center: WHITE SANDS
Phone: (505)-524-5517, Ext ______	Mail Stop:	
Short Title: ET LOX Feedline Bellows Baseline vs Drip Lip Testing		
Description: From the initiator's e-mail: Objective: Develop and conduct tests to determine the integrity of ice that forms at the LOX feedline bellows area comparing the original beveled design to the new 10 degree drip lip design for the purpose of evaluating debris potential during launch.		
Source (e.g. email, phone call, posted on web): e-mail		
Type of Request: Consultation		
Proposed Need Date:		
Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm):		
Section 2: Systems Engineering Office Screening		
Section 2.1 Potential ITA/I Identification		
Received by SEO: (mm/dd/yyyy h:mm am/pm): 1/19/2005 12:00 AM		
Potential ITA/I candidate? ☐ Yes ☒ No		
Assigned Initial Evaluator (IE):		
Date assigned (mm/dd/yyyy):		
Due date for ITA/I Screening (mm/dd/yyyy):		
Section 2.2 Non-ITA/I Action		
Requires additional NESC action (non-ITA/I)? ☒ Yes ☐ No		
If yes:		
Description of action: Approved Out-of Board; Provide status		
Actionee: Mike Kirsch		
Is follow-up required? ☒ Yes ☐ No If yes: Due Date: Documents need to be submitted by 01/27/2005 for the NRB on 02/03/2005		
Follow-up status/date: Present status at NRB 02/03/2005		
If no:		
NESC Director Concurrence (signature):		
Request closure date:		

Section 3: Initial Evaluation			
Received by IE: (mm/dd/yyyy h:mm am/pm):			
Screening complete date:			
Valid ITA/I candidate? ☐Yes ☐ No			
Initial Evaluation Report #: NESC-PN-			
Target NRB Review Date:			
Section 4: NRB Review and Disposition of NCE Response Report			
ITA/I Approved: ☐Yes ☐ No	Date Approved:		Priority: - Select -
ITA/I Lead: , Phone ( ) - , x			
Section 5: ITA/I Lead Planning, Conduct, and Reporting			
Plan Development Start Date:			
ITA/I Plan # NESC-PL-			
Plan Approval Date:			
ITA/I Start Date	Planned:	Actual:	
ITA/I Completed Date:			
ITA/I Final Report #: NESC-PN-			
ITA/I Briefing Package #: NESC-PN-			
Follow-up Required? ☐Yes ☐ No			
Section 6: Follow-up			
Date Findings Briefed to Customer:			
Follow-up Accepted: ☐Yes ☐ No			
Follow-up Completed Date:			
Follow-up Report #: NESC-RP-			
Section 7: Disposition and Notification			
Notification type: - Select -	Details:		
Date of Notification:			
Final Disposition: - Select -			
Rationale for Disposition:			
Close Out Review Date:			

NESC Request Form
NESC-PR-003-FM-01, v1.0

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Form Approval and Document Revision History

Approved: ______________________________ __________
NESC Director Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineers Office	29 Jan 04

Plan Approval and Document Revision History

Approved:	Original signature on file	9/22/05
	NESC Director	Date

Version	Description of Revision	Author	Effective Date
1.0	Initial Release	Principal Engineer's Office	